УДК 550.388.2

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EVOLUTION OF A TOXIC CLOUD THAT WAS FORMED BY AN EXPLOSION OF A CARRIER ROCKET

The model which describes an explosion of a carrier rocket “Proton”, evolution and flight of a cloud of sprayed propellant are created.

1. Introduction

Alexandrov [1] has developed the model of evaporation of separate dimethyl hydrazine (1,1-DMH) drop in the atmosphere, and he has determined altitudes, starting with which the remaining propellant do not reach the surface of the Earth. The purpose of the work is to describe the evolution of a toxic cloud that was formed by an explosion of a carrier rocket (CR) “Proton” at different heights.

2. Model

It is known from experiment [2] that the effect of a shaped explosive charge of arbitrary form at the distances exceeding its characteristic size is equivalent to the effect of a spherical charge of the same mass. At the length of the charge being much more than its sizes in two other directions, this condition holds true for the distance of several charge length. Taking into account the fact that the expected dispersion of fuel particles under the effect of explosion may cover hundreds of meters and the diameter of a rocket is a few meters, we consider the explosion as point, and the dispersion of fuel in space to be closed to spherical one. We also take into account the fact that fuel dispersion - extension of the cloud – may also take place on account of vapor pressure as a result of fuel evaporation. The conservation law of momentum for the given case we write in the form

$$\frac{d\left[\left(M_a+M_t\right)*v\right]}{dt}=s\left(p_1+p_v-p_a\right), \qquad (1)$$

where $M_a=\frac{4}{3}\pi\rho_a\left(r^3-r_0^3\right)$ is the mass of air involved into a shock wave movement, ρ_a is the air density depending on the height, r is the current radius of the cloud, r_0 is the initial radius of the cloud determined from the volume of fuel at the moment of explosion. $M_t=\frac{4}{3}\pi\rho_t r_0^3$ is the mass of fuel at the moment of explosion, ρ_t is density of fuel. $s=4\pi r^2$ is interface area of the cloud of fuel, p_1 is pressure in the cloud due to explosion, p_v is pressure in the cloud generated by the vapor of the evaporated fuel, p_a is atmospheric pressure at the given height. According to the experiment [2]

$$p_1=4\pi r_0^2 p_x\left(\frac{r}{r_0}\right)^{2-3\gamma}, \qquad (2)$$

where up to $r=2r_0 \to \gamma=3$, and further $\gamma=1.25$. $p_x=2\rho_t\frac{E}{M_t}$ is initial pressure at the interface, $E=Q*4.15*10^6$ J is the initial energy being released due to explosion, Q is trinitrotoluol equivalent (TNT): 1 kg of 1,1-DMH corresponds to 0.57 kg TNT (the energy consumed for the destruction of the rocket structure is neglected). Let us assume that on account of fuel evaporation, the concentration of vapor reaches the concentration of saturated vapor. In this case, one may use an empirical expression to determine the vapor pressure [3]

$$p_v=\exp\left(23.663-\frac{4075.6}{T}\right),\ \text{Pa}, \qquad (3)$$

where T is Kelvin temperature, and the vapor density

$$\rho_v=\frac{0.9643}{T}\exp\left(\frac{16.787T-3445}{T-52.27}\right),\ \text{kg/m}^3. \qquad (4)$$

At the initial stage of the cloud extension, the mass of the involved air may be neglected compared to the mass of the fuel. In this case, one may derive the following differential equation describing the dependency of vapor content ($\alpha=\frac{M_v}{M_t}$, M_v is mass of vapor) on temperature [4]

$$\frac{d\alpha}{dT}+\left(\frac{C_v-C_t}{\lambda}\right)\alpha+\frac{C_t}{\lambda}=0, \qquad (5)$$

where $C_v = 7.*10^{-23}$ J/K is heat capacity of one molecule of 1,1-DMH vapor, $C_t = 3*10^{-22}$ J/K is heat capacity of one molecule of 1,1-DMH liquid, $\lambda = 5.43*10^{-20}$ J is heat of change of phase transitions per one molecule. From the conservation equation of substance we may have:

$$\frac{\alpha(T)}{\rho_v(T)} = \frac{4\pi r^3}{M_t}. \qquad (6)$$

Equations (1) - (6) completely describe the changing of radius of the cloud with time under the effect of explosion and vapor pressure of the evaporated fuel. They also allow determining the temperature in the cloud with time, density of vapor and its percentage. The flight trajectory of a cloud is determined by the kinetic momentum of a particle due to the explosion, vapor pressure, the movement of the rocket, the attractive force of the Earth and resistance force of the atmosphere. We neglect by Archimedes force of buoyancy because density of the propellant is much more than density of air. The resistance force of the atmosphere is opposite to the direction of the velocity of a body, and the value of this force depends, among other things, on the geometry of the body. For a sphere it is determined by the Stock's law formula

$$R = 0.5 \rho c_x s_m V^2, \qquad (7)$$

where ρ is atmospheric density; c_x is dimensionless coefficient depending on a Reynolds number $Re = \frac{2r\rho V}{\eta}$; s_m is the area of the greatest section of a body; V is the absolute value of the velocity of moving of a body relative to the atmosphere, r is radius of a sphere, η is viscosity. The dependence c_x(Re) is determined experimentally for liquid and gaseous media. Knowing the change of cross surface $S = \pi r^2$ with time we can write the equation of the body movement:

$$\frac{dV_z}{dt} = 0.5 \frac{\rho(t)}{m} c_x S(t) V^2(t) \cos\theta_z - g, \qquad (8)$$

$$\frac{dV_x}{dt} = -0.5 \frac{\rho(t)}{m} c_x S(t) V^2(t) \cos\theta_x, \qquad (9)$$

$$\frac{dV_y}{dt} = -0.5 \frac{\rho(t)}{m} c_x S(t) V^2(t) \cos\theta_y, \qquad (10)$$

where: x-axis is direction to the East, z-axis is the upward direction, and y- axis is direction to the North; $\cos\theta_z = V_z(t)/V(t), \cos\theta_x = V_x(t)/V(t), \cos\theta_y = V_y(t)/V(t)$.

The origin of coordinates is choosing in a point of explosion of the rocket, so that

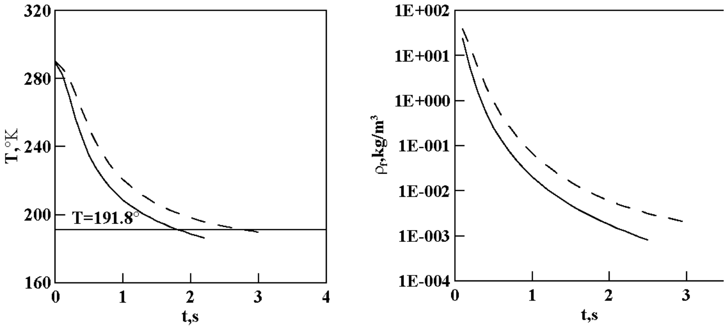
$$z(t) = \int V_z dt, \; x(t) = \int (V_x + W_x) dt, \; y(t) = \int (V_y + W_y) dt, \qquad (11)$$

where W_x and W_y – zonal and meridional components of wind, respectively. Zero time reference is the moment of explosion.

3. Results

The solution of a set of equations (1) - (11) was carried out numerically. The program also uses the following data: propellant consumption along the trajectory, model of the atmosphere MSIS-93 [5], model of the horizontal wind HWM-93 [6], experimental dependency of factor c_x on a Reynolds number, etc. To demonstrate the work of the program and analyze of the physical processes let us consider the explosion of the rocket "«Proton" of October 27, 1999 (place of the launch was Baikonur). The rocket launch was produced at 16 mines past 9 UT, and the explosion took place at the altitude of 93 km on 222 seconds. The calculations are carried out for explosion of 100 kg of propellant. We have assumed that all remaining propellant of second and third stage of the launcher will simultaneously be ejected into the atmosphere during the explosion; and temperature of propellant in the tanks at the moment of explosion is equal to the temperature on the ground surface at the moment of the launch - 290°K. We have neglected by combustion of propellant for calculation of the greatest possible contamination of the atmosphere. During calculations we used dependence of the weight of propellant in tanks of the launcher on the flight time. Fig. 1a represents the results of calculation of temperature of the cloud depending on time. We can see that the temperature decreases to 191.8?K in 1.8 s after the explosion. This temperature corresponds to temperature of freezing of propellant drops. Then the evaporation sharply slows down.

The density of propellant - ρ_f in the cloud decreases to the value of 2.5 10^{-3} kg/m^3, exceeding the atmospheric density at height of explosion by a factor of 10^3 (2.2 10^{-6} kg/m^3). This justifies the assumption of smallness of mass of the involved air in comparison with the mass of fuel used when deriving (5). The time dependence of the relative contents of vapor and pressure of vapor in the cloud is presented in Figure 2. It is seen in the Fig. 2a that the main transition of the liquid into vapor takes place in the first seconds after the explosion, and the curve



a b

Fig. 1. Dependence of temperature (a) and density of propellant (b) in the cloud on time during the first seconds after explosion. A solid line - for the height of 93 km, dashed line- for the height of 45 km

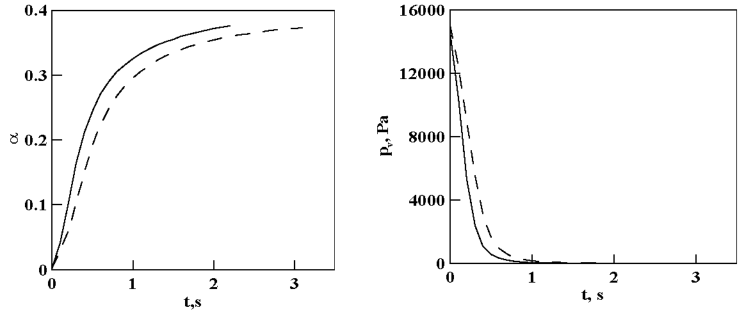


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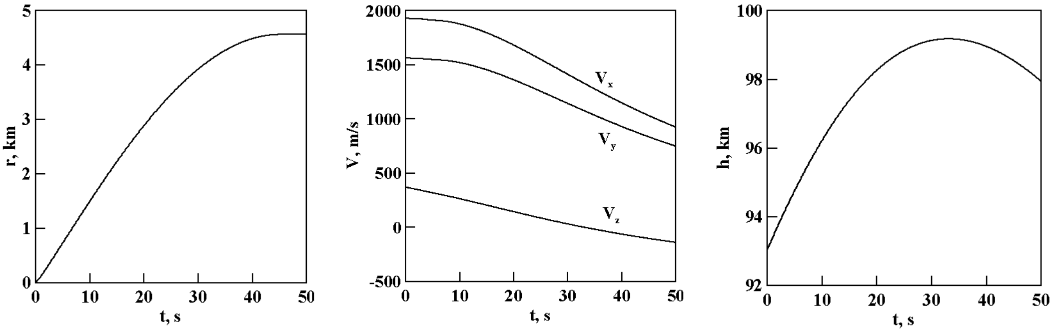
Fig. 2. The relative content of vapor (a) and pressure of vapor (b) in the cloud in the first seconds after the explosion. A solid line - for the height of 93 km, a dashed line- for the height of

tends to saturation. The content of the vapor does not exceed 38 % in the

moment of freezing of drops. It is not possible to trace the movement of vapor molecules in space. Because of small weight of molecules, their scattering will be caused by accidental processes. In any case it is impossible to expect their fast falling onto the earth surface. In this connection we will pay attention mainly to processes taking place with the drops of propellant, because they have considerably larger sizes and weight.

We can see in Figure 2b that the pressure of vapor sharply decreases in the first seconds after the explosion. Further, after freezing of liquid, its effect may be neglected and only pressure caused by explosion is taken into account. The Fig.

3a shows the radius versus time. Practically, in 45 seconds after the explosion the pressure in the cloud reduces up to atmospheric and the process of the cloud due to explosion comes to the end. Simultaneously, the horizontal velocity of cloud movement decreases approximately twice, and along vertical in close to zero (Fig. 3b), at the same time the height of a cloud disposition of begins to decrease (Fig. 3c). At the 45s the cloud is at the height of 98.5 km, where the atmospheric density is approximately 6 10^{-7} kg/m^3. Density of propellant in a cloud has approximately the same magnitude to this moment. In this connection it is impossible to neglect the exchange of heat between fuel and air in the volume. Temperature at the height of 98.5 km is approximately 185K. That is lower than melting point of 1,1-DMH - 215K [3]. It means that under conditions of leveling off the temperature the transition of the cloud crystals into a liquid phase will not take place. It is interesting to compare the above-stated calculation results with similar ones for height of the 45 km, where approximately the active flight of the carrier rocket begins: the second stage begins to work. The main difference is in the greater atmospheric density (pressure) at the height 45 km - it is 2* 10^{-3} kg / m^3. As a result «resistance" of atmosphere to the process of the cloud extension is much greater. The radius of the cloud reaches the value of only 320м against 4560м (Fig. 3a) at the height 93 km. Time of the cloud extension decreased: 4 s and 45 s, respectively. Simultaneously the velocity of the cloud extension at the height of 45 km was less than that at the height of 93 km. As a result the process of the temperature decrees in the first case was slower than in the second one (Fig. 1a), and it lasted 1s more. Process of vapor pressure decrease as well as the process of saturation of the cloud with vapor (Fig. 2) was accordingly delayed. At the same time the final contents of vapor



a b c

Fig. 3. The change of radius (a), velocity (b) and height of the cloud (c) with time

remained approximately the same. The velocity of the cloud movement at the height of 45 km considerably decreases as well as for the height of 93 km, however the vertical component of velocity is not zero due to a substantially greater value of vertical speed of the rocket at the moment of the explosion. It leads to the further ascent of the cloud due to inertia. Temperature of the atmosphere at the height of 47 km is 261?K, which is higher than the melting point of 1,1-DMH - 215?K. It means that the crystals should thaw, and further it is necessary to consider the evolution and movement of drops of the liquid.

Dropping structure of a cloud.

The pressure in the cloud is equalized up to atmospheric after explosion, and it ceases to expand. The force of resistance of atmosphere to process of the cloud expansion disappears. At the same time there is the effect of force of the Earth gravitation and the momentum of motion due to the rocket launcher. During this stage of the cloud evolution we will consider behavior of separate drops and their trajectories of motion. First of all, we shall define the mechanism of splitting of fluid; for what we shall evaluate the value of Bond's criterion [7] $Bo = 4r^2\rho_t a/\sigma$, where r is radius, ρ_t is density of propellant, **a** is acceleration, σ is surface tension. Initial equivalent radius of volume of ejected propellant has value about 10 m at the altitudes 45 - 100 km. Density of 1,1-DMH has value about 800 kg / m^3; surface tension is about 0.026 N/m. Acceleration of the fluid motion at the time of explosion can have value from tens up to hundreds meters per second. As a result we obtain Bo=10^8-10^9. In accordance with [7], when Bo>$5*10^3$ the mechanism of explosive destruction of fluid onto drops should be realized. This mechanism usually associates with instability of Raleigh - Taylor, developing on a windward side of fluid. Except for an action of explosion onto process of splitting of fluid onto drops, the flow of air (due to the motion of a cloud in the space) and evaporation also should affect this process. At such scheme of splitting of fluid onto drops, it is a big problem to calculate time of splitting. At the same time, the duration of process of the expansion of a cloud under an action of explosion at altitude of 90 km is tens seconds and more (Fig.3a), at altitude of 45 km - a few seconds and more, and during this time about 40 % of fluid is evaporated (Fig.2a) - it is possible to assume, that to the moment of pressure equalization in a cloud and ambient atmosphere all fluid will be spitted onto drops. Really, if to take into account only mechanism of splitting of fluid due to inertial motion of a cloud (speed is about kilometer per second), then the characteristic time of splitting can be calculated using formula $t_* = \frac{2r}{V}\left(\frac{\rho_t}{\rho}\right)^{1/2}$. As a result, we obtain value t* about 100 s for altitude of 90 km, and about 2 seconds for 45 km. Obviously, effect of an explosion and process of evaporation should essentially reduce this time. Investigation has shown (Fig.1a) that due to process of evaporation the liquid is transformed into a crystalline phase. In this connection, it is possible to assume, that their freezing happens simultaneously with the process of splitting of fluid on drops. Then at the further solution of the problem, we will trace motion of separate frozen drops in the space. The critical size of drops is determined by formula $r_k = \frac{\pi}{2}\sqrt{\frac{\sigma}{\rho_t g_s}}$, where g_s is acceleration of motion of fluid; $\sigma=5.88*10^{-2}$-$1.157*10^{-4}T$ (N/m), $\rho_t = 785 - T + 293$(kg/m^3). It is important to note the relation of σ/ρ_t varies in the range of temperatures a little: 1.3 times in the range from 191.8°K up to 300°K. Further, as we can see in Fig. 3b, the speed of motion of a cloud begins sharply to decrease after the explosion, and this decreasing of speed happens, practically, linearly. It means that during stage of splitting of liquid the acceleration also varies a little, and hence the range of changes of the critical size of drops cannot be large. In this connection we will calculate the critical size of drops at the instant of the termination of process of cloud expansion. As a result r_k=2.4 mm for the height of 93 km and r_k=1.3 mm for 45 km. It is supposed [1] that after splitting of liquid; the drop size distribution function is close to exponential $f(r) = A\exp(-1.56r)$, where $A = \dfrac{1.56}{1-\exp(-1.56r_k)}$ is a normalizing multiplier. According to this distribution it is possible to calculate percent of number and weight of drops for separate intervals of the sizes. The investigation shows that the basic part of propellant is focused in drops of the greater size. The propellant splits onto drops of the smaller size at smaller height. It is caused by the greater density of the atmosphere at lower heights; as a result the braking of a cloud occurs faster.

Process of heating and melting of crystals

During falling in the atmosphere the crystals will be heating and melting. We shall calculate trajectories of their falling on the basis of formulas (8) - (10). We use the following equation of thermal balance to describe the temperature dependence on the time [4,8]

$$mc_s\frac{dT}{dt} = -4\pi\lambda \;\; r\left(T - T_a\right)F_vF_{kn}, \qquad (12)$$

where m is weight of a particle; c_s =2.68 kJ/kg*K is thermal capacity of 1,1-DMH; λ is heat conductivity of air; T is temperature of a particle; T_a is temperature of the atmosphere; $F_v = 1 + 0.22\,\mathrm{Re}^{1/2}$ and $F_{kn} = \dfrac{\exp(Kn)}{1 + 4/3Kn\exp(Kn)}$ are the factors which are taking into account a mode of heat exchange depending on speed of movement of a particle and a mode of flow; $Kn = l/(2r)$ is Knudsen's number; l is length of free run of molecules of air. At temperature T=215 K and the heat (Q) inflow sufficient for melting the crystal

$$Q = c_p m \quad 4\pi\int\lambda\left(T - T_a\right)F_vF_{kn}dt\,, \qquad (13)$$

1,1-DMH will pass to a liquid phase, and will fall further as a drop of a liquid; where in (13) c_p is the specific heat of melting 1,1-DMH.

The result of calculation of crystal temperature is given in Fig. 4. The calculation was carried out for the explosion at the height of 93 km and the critical radius of a drop equal to 2.4 mm. The crystal has flown from height of 96.5 km up to height of 54.1 km during 113.2 s. The temperature of a crystal grows till the moment of the beginning of its melting, and then remains constant as long as the crystal melts. Thus, the drop falls during the significant part of the trajectory as a crystal.

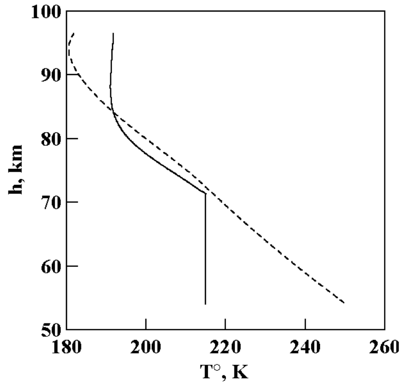


Fig. 4. Change of temperature of a crystal with height in the process of its falling (solid line) and temperature of the atmosphere (dotted line).

4. Conclusion

The complex of physical phenomena, which accompany explosion of a rocket, initial process of formation and evolution of a toxic cloud, sequentially, is considered. The temperature of propellant drops of the cloud decreases to 191.8?K (due to evaporation) in a few seconds after the explosion. This temperature corresponds to temperature of drop freezing. When the cloud goes down to the height of 50 km, the temperature of the atmosphere increases to 260?K, which is higher than the melting point of 1,1-DMH - 215?K. It means that the crystals should thaw, and further it is necessary to consider the evolution and movement of drops of the liquid.

Работа выполнена в рамках НИР по Государственной программе «Развитие космической деятельности в Республике Казахстан на 2005-2007 годы» (контракт № 311 от 13.03.2006), а также гранту ISTC проект No K-451.2.

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Резюме

Зымырантасығыштың ұшу траекториясының белсенді аумағындағы жарылысы кезінде пайда болған бұлттың түзілу үрдісі мен эволюциясы қарастырылған.

Резюме

Рассмотрены процессы формирования и эволюции токсичного облака, возникшего при взрыве ракеты-носителя на активном участке траектории полета.

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